



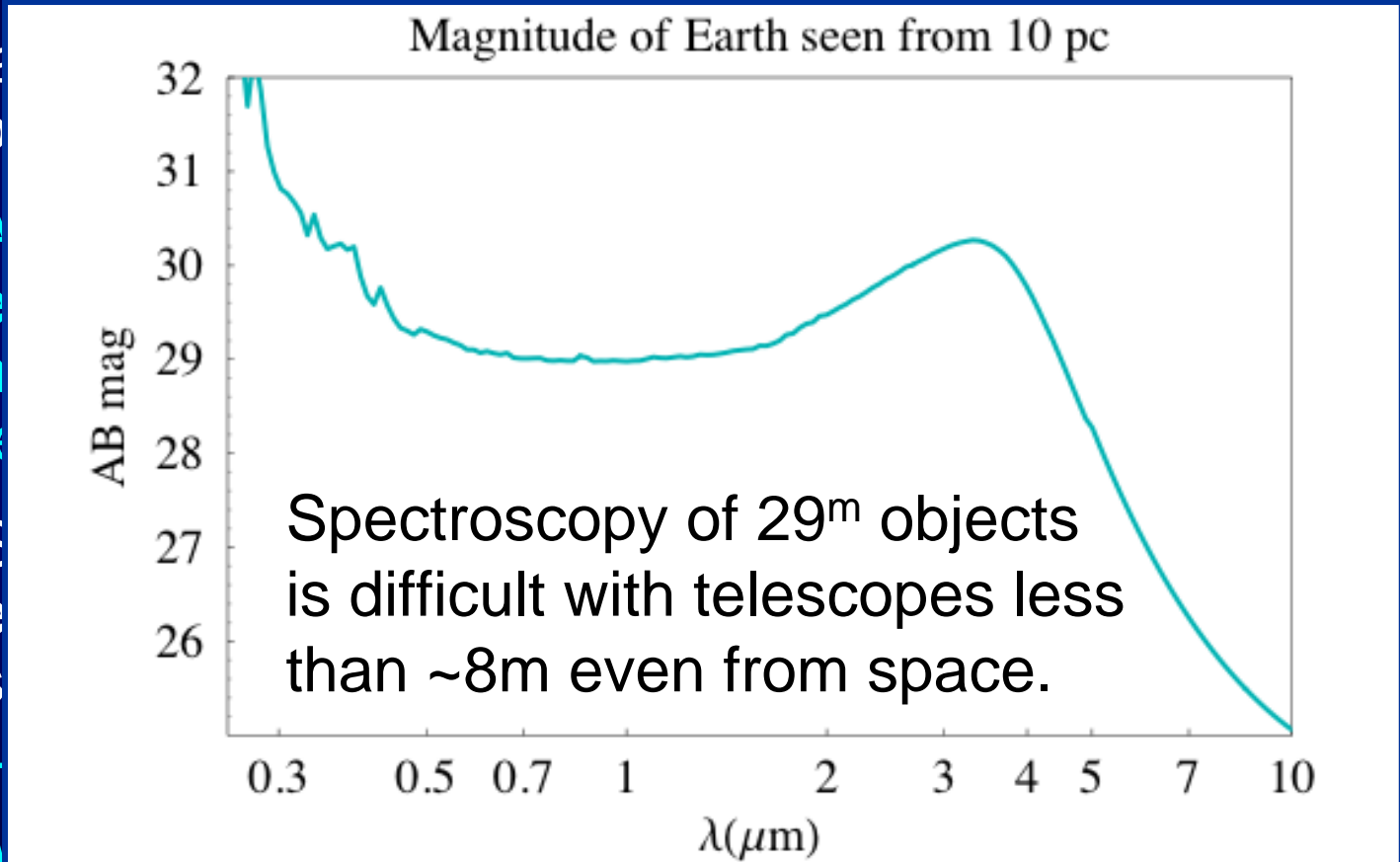
Characterizing Earth-like Exoplanets with Space Telescopes

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Motivation

- The most compelling scientific problem for the next



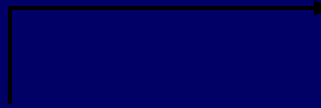
- Spectroscopy of 29^{m} objects is difficult with telescopes less than $\sim 8\text{m}$ even from space.

- The

When you add the reach of any existing telescope for spectroscopy

The magnitude of the problem

The interesting region



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Earth as viewed by Voyager



The Earth's Atmosphere

Cloud-free

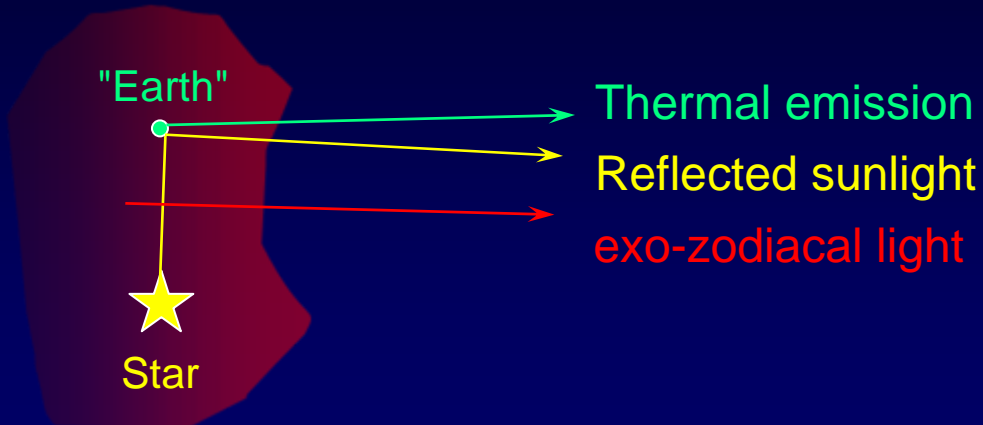
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Kaltenegger, Traub, & Jucks 2007, *Ap.J.*, **658**, 598

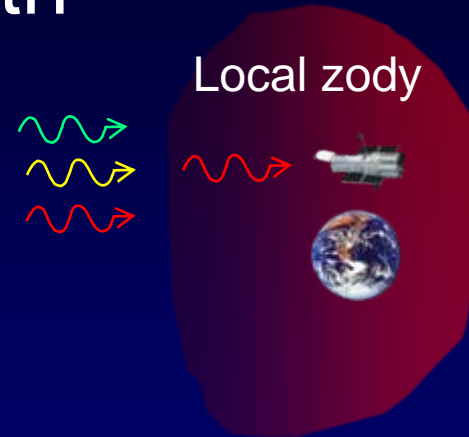
Characterizing Atmospheres

- Direct spectra (single telescopes, interferometers, w/ or wo/ aids like occulters)
 - Req. 1D: capture the faint light from the planet
 - Req. 2D: suppress unwanted light from the bright star & local background radiation ($\sim 10^{-10}$)
- Transmission spectra through transit observations
 - Req. 1T: capture enough starlight to distinguish tiny ($\sim 10^{-7}$) differential changes in the light curves
- Requirement 1D effectively limits the distance a telescope of a given collecting area can detect Earth.
- Requirement 2D is a constraint on the optical system.
- Requirement 1T is driven more by the contrast requirement than the stellar brightness.

Direct Detection of exo-Earth



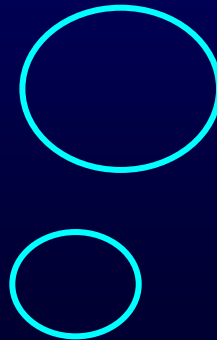
Photon statistics of the earth signal
and background (zody + exo-zody)
set the natural detection limits:



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$$D_{max} \sim 40\text{pc } \eta^{1/2} d_{tel}/8\text{m}$$

Observation of Earth @ 10 pc

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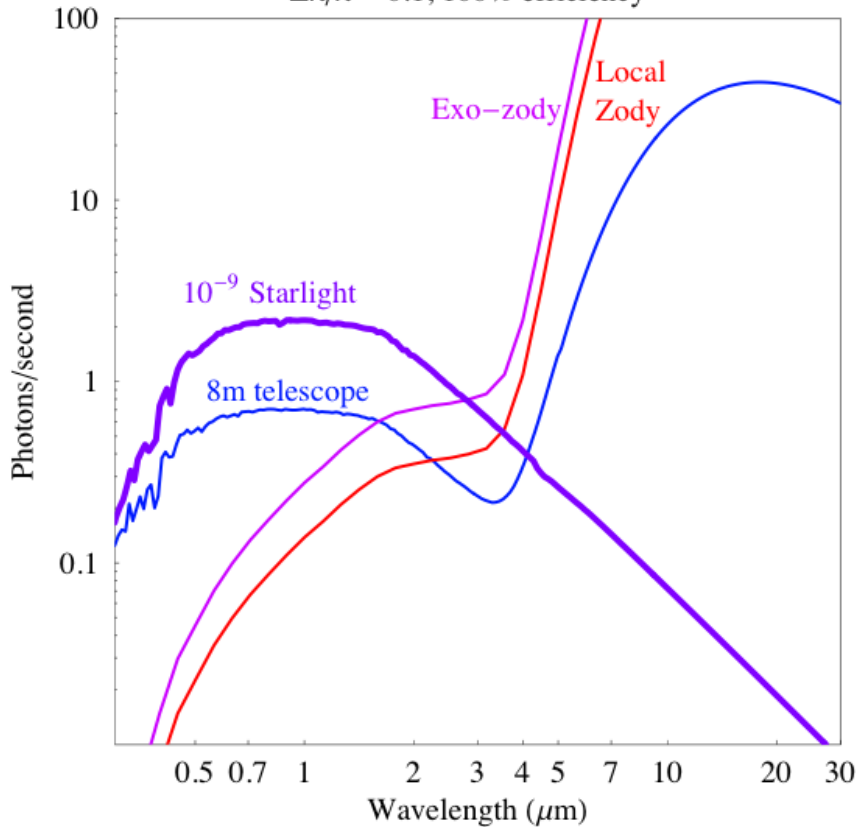
Includes exo-zody

Photometric detection

Spectroscopic study

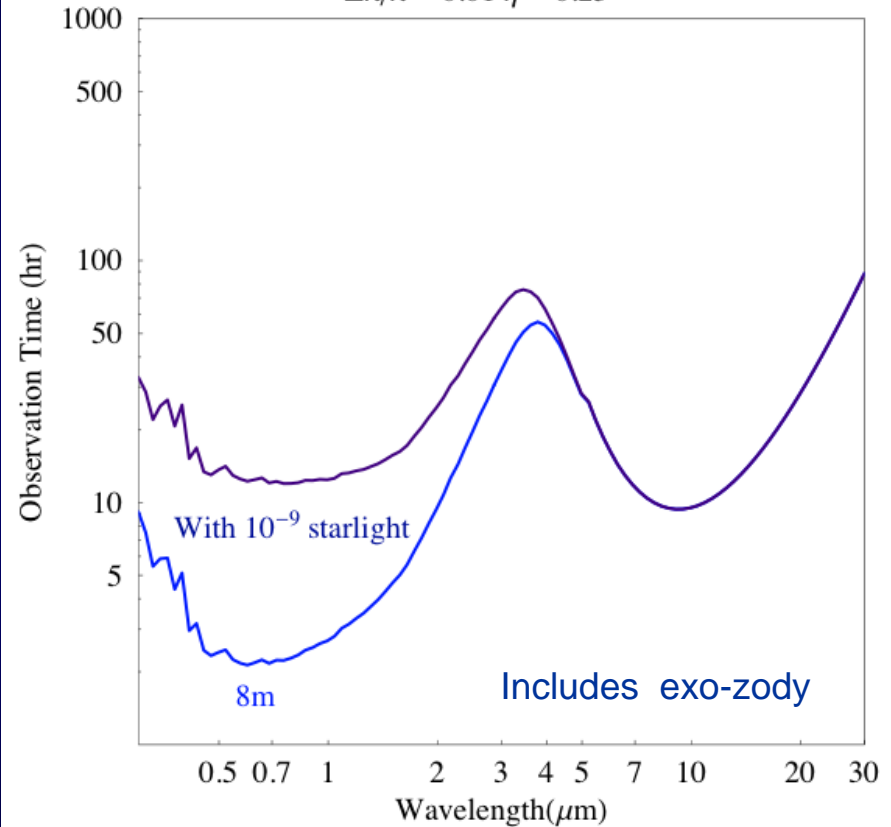
Effect of uncanceled starlight

Photon rate for Earth at 10. pc
 $\Delta\lambda/\lambda = 0.1$, 100% efficiency



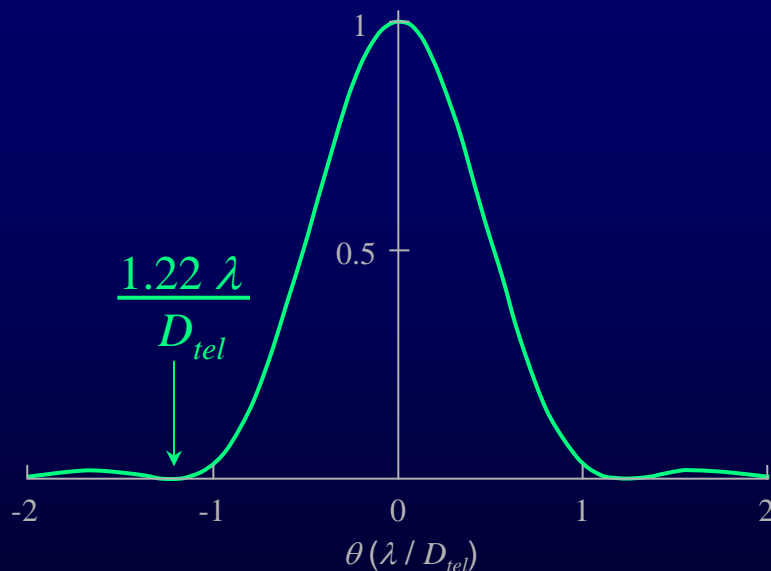
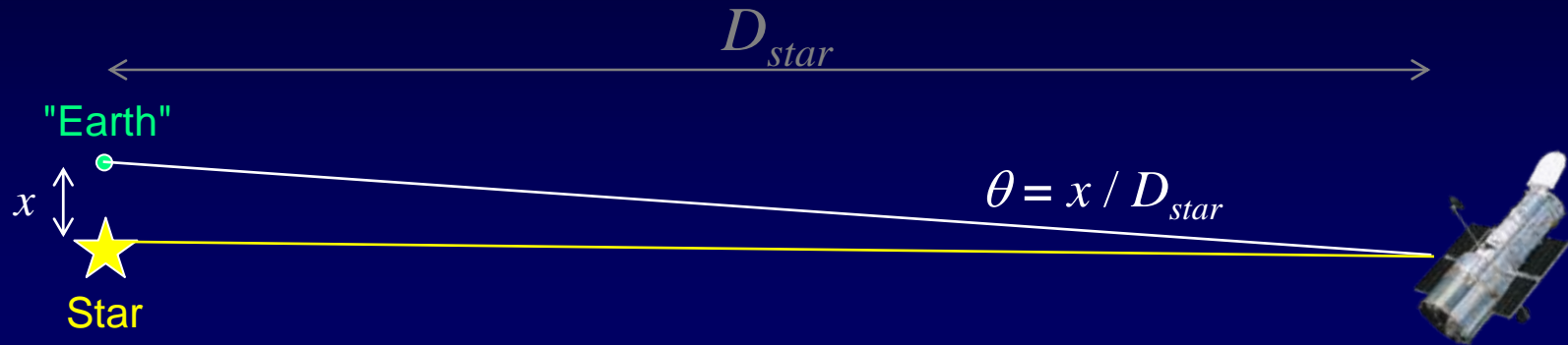
Photometric detection

Earth at 10. pc, S/N = 10
 $\Delta\lambda/\lambda = 0.01$ $\eta = 0.25$



Spectroscopic study

Suppressing the Starlight



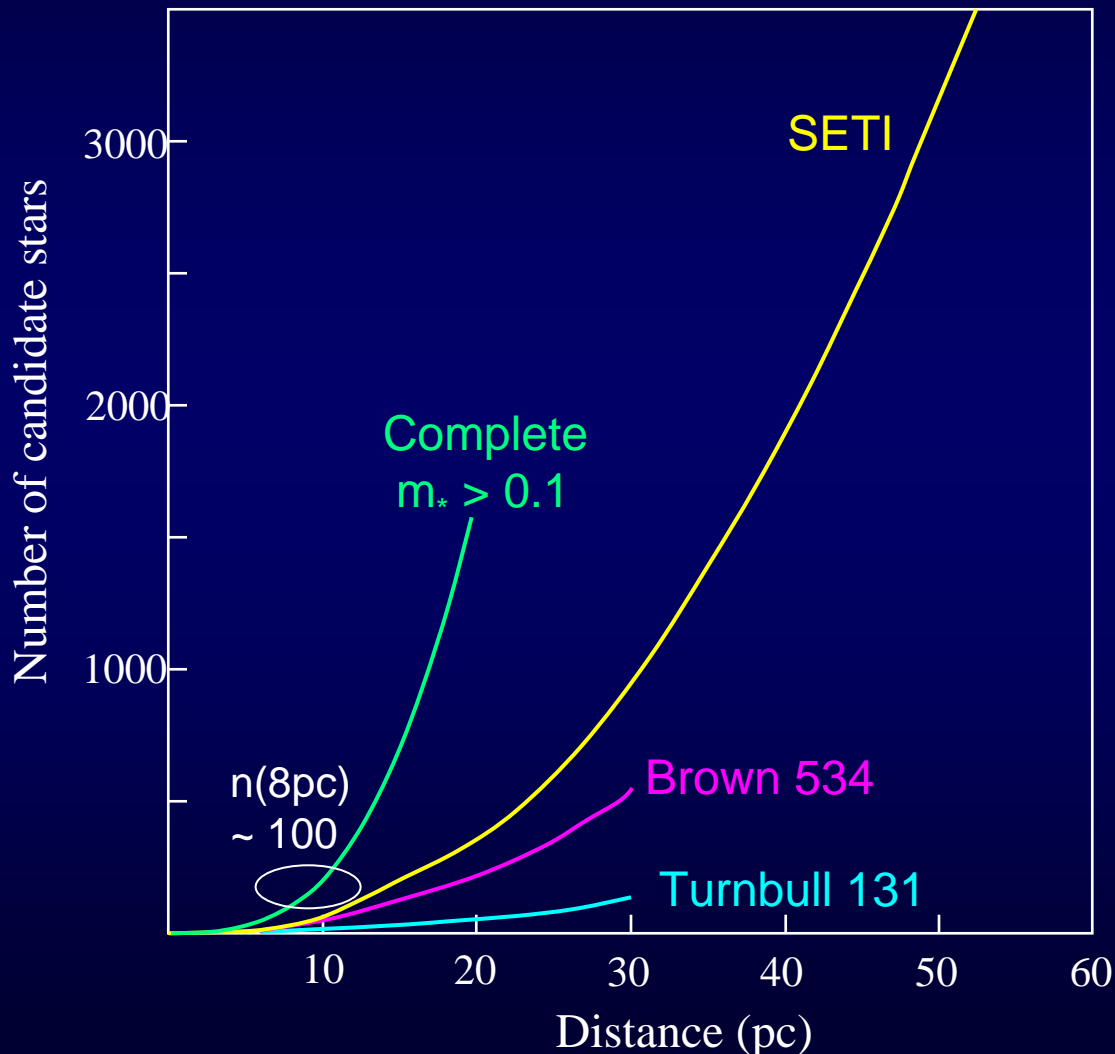
Smallest possible inner working angle for a circular telescope: $\theta_{airy} = 1.2 \lambda / d_{tel}$

Practical designs give

$$\theta_{IWA} \sim 3-4 \lambda / d_{tel}$$

Define: $\theta_{IWA} = X \theta_{airy}$
 $= X 1.2 \lambda / d_{tel}$

Samples of local stars



- Turnbull/Brown select nearby G & K stars
- Complete sample stars are mostly M dwarfs
- SETI sample is from Turnbull & Tarter 2003: ~18,000 to 2 kpc

Habitable Zone:

$$r_{in} = \left(\frac{L_{star}}{16 \pi \sigma_{sb} (373)^4} \right)^{1/2}$$

$$r_{out} = \left(\frac{L_{star}}{16 \pi \sigma_{sb} (273)^4} \right)^{1/2}$$

$$\log \left[\frac{r_{out}(\text{HZ})}{r_{in}(\text{HZ})} \right] = 0.27$$

Sample Growth vs. Telescope Size

$$\theta_{IWA} = 25 \text{ mas } (10\text{m} / d_{tel})$$

$$N_{vol} \sim D_{max}^3 \\ \sim d_{tel}^3$$

But, $\theta_{IWA} \sim d_{tel}^{-1} \Rightarrow$
increases sample
through lower
luminosity stars
with smaller
Habitable Zones

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decompressor
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$$\theta_{IWA} < r_{out}(\text{HZ})$$
$$\theta_{IWA} < r_{in}(\text{HZ})$$

$$N \sim d_{tel}^{3.3}$$

Parametric sample analysis

MS stellar parameters & PDMF allow the sample sizes to be expressed in terms of stellar mass & planet temperature

Stellar
parameters

$$R_p = \left(\frac{L_*}{16 \pi \sigma_{sb} T_p^4} \right)^{1/2}$$

HZ radii

$$R_p = \frac{1}{2} \left(\frac{T_*}{T_p} \right)^2 r_*$$

$$\alpha_m = 1.1 (m \leq 1) \\ = 5.2 (m > 1)$$

Present Day
Mass Function

Sample size vs.
stellar mass

Sample size vs. observing parameters

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$$\theta_{IWA} = X \theta_{airy}$$

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Coronagraph: $X = 2$

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Occulter: $X = 1$

Interferometer: $X = 0.1$

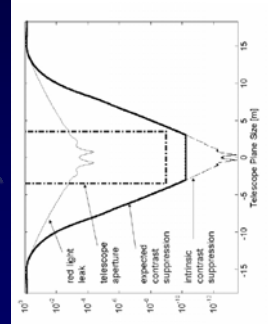
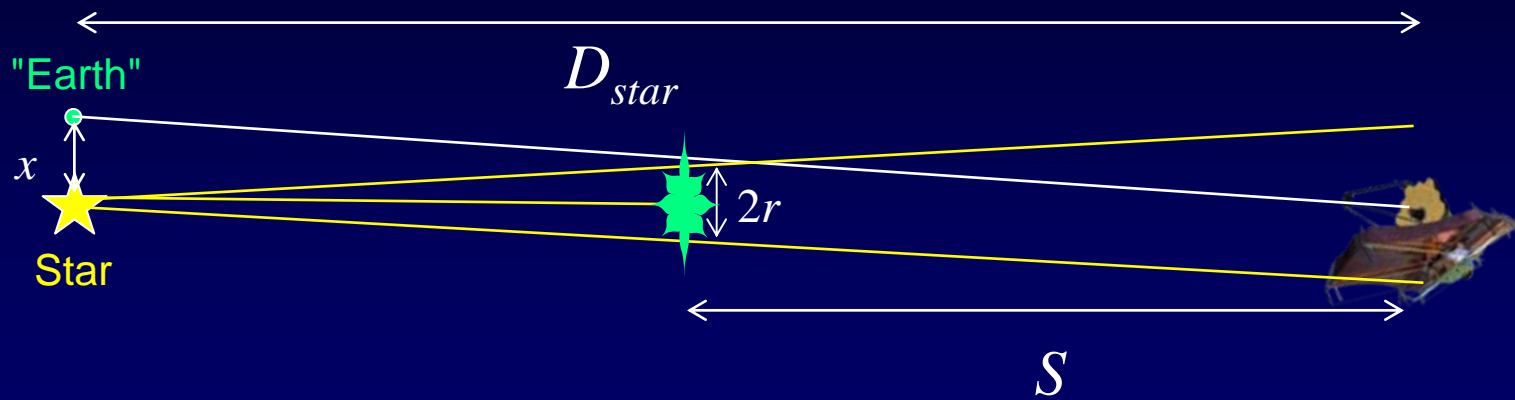
These samples include all star systems. The number of stars suitable for life will be some fraction of the samples.

Coronagraphic samples

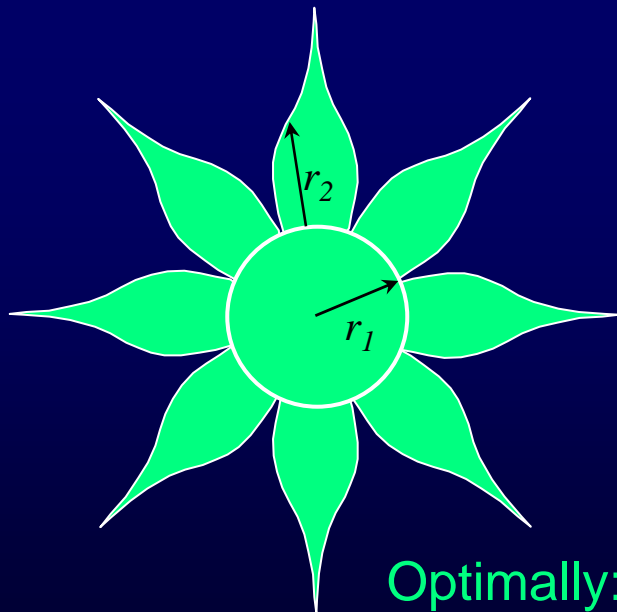
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External Occulter (New Worlds Observer)



Petal shape: $T(\rho) = \exp[- (\rho - r_1) / r_2)^n]$ for $\rho > r_1$



Optimally:

$$r_1 = r_2 = r$$

Inner Working Angle: $\theta_{IWA} = (r_1 + r_2) / S$

Contrast: $C = [(n!)^2 (\lambda S / 2\pi r_1 r_2)^{2n}]^2$

To study planets we want:

$\theta_{IWA} < x / D_{star}$ (small θ_{IWA})

$C < 10^{-10}$ (small contrast)

Optimizing r & D

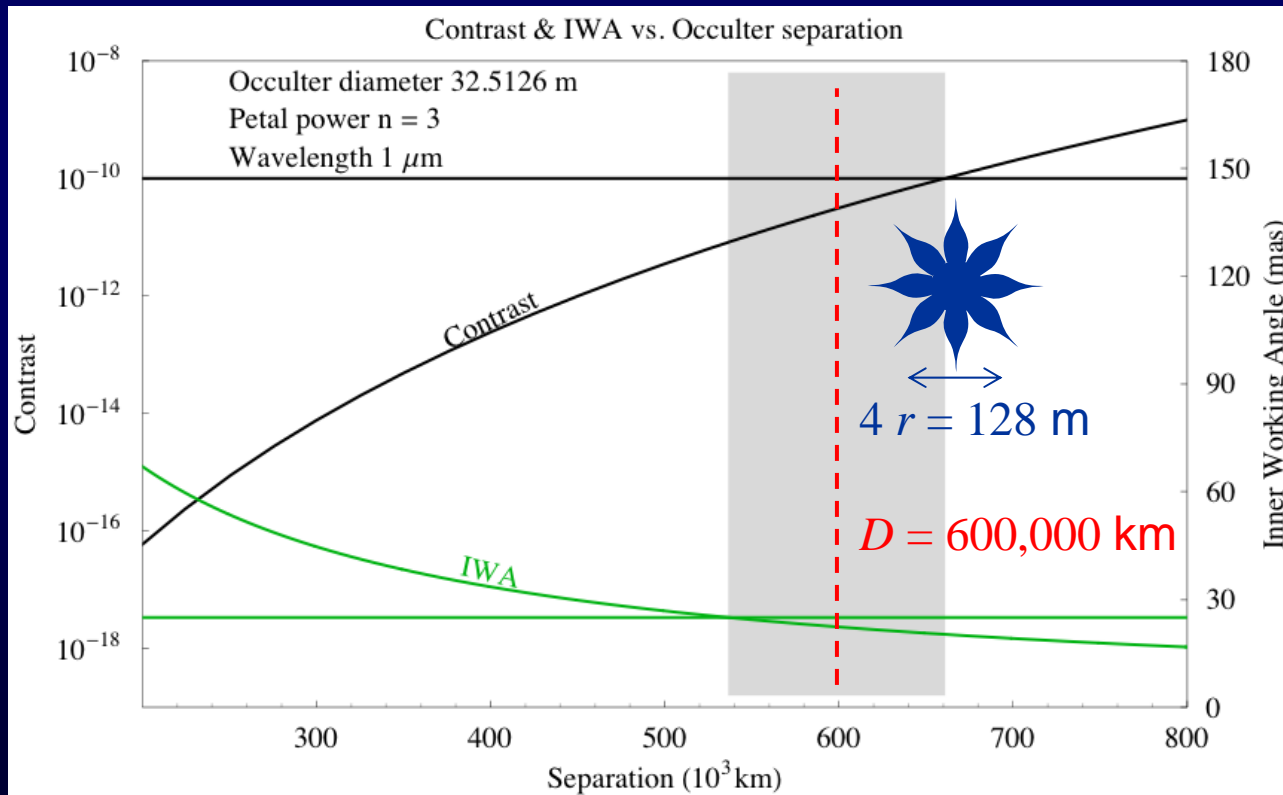
$$\theta_{IWA} = 2 r / S \sim 25 \text{ mas}$$

$$C = [(n!)^2 (\lambda S / 2 \pi r^2)^{2n}]^2 \sim 10^{-10}$$

$$r = (n!)^{1/n} \lambda / (\pi \theta_{IWA} C^{1/4n})$$

$$r = 32.5 \text{ m } \lambda_{\mu\text{m}} (\theta_{IWA} / 25 \text{ mas})$$

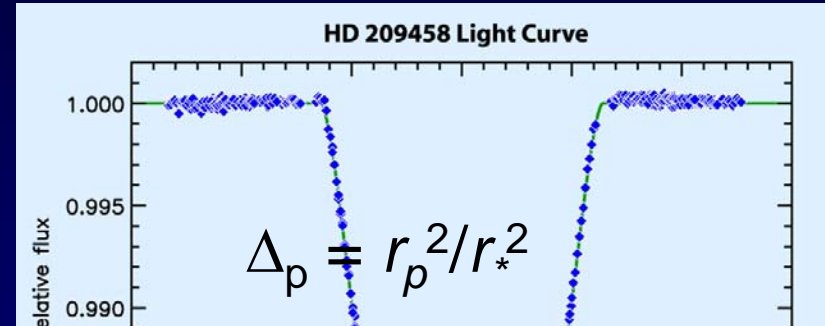
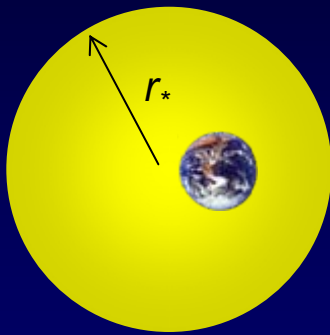
$$S = 540,000 \text{ km } \lambda_{\mu\text{m}} (\theta_{IWA} / 25 \text{ mas})^{-2}$$



$$n = 3$$

$$C = 10^{-10}$$

Transit spectroscopy

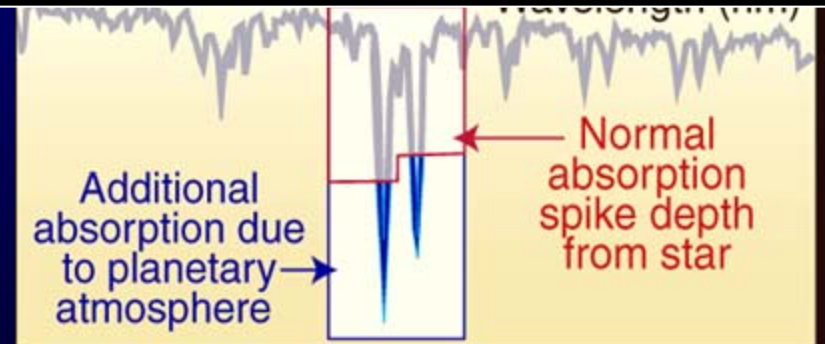


Signature is independent of planet size to first order (\sim density): increasing r_p (mass) decreases scale height, h_{atm} .

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Scale height factor vs. optical depth: $x \approx 4.2 + \ln \tau_0$

Transit spectroscopy

Sensitivity of transit spectroscopy *increases* as the stellar mass (temperture, size) *decreases*: the sample is dominated by low-mass stars.

$$\frac{\sigma_{N_\gamma}}{N_\gamma}$$

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$$D_{max} \sim d_{tel}$$

Transit samples

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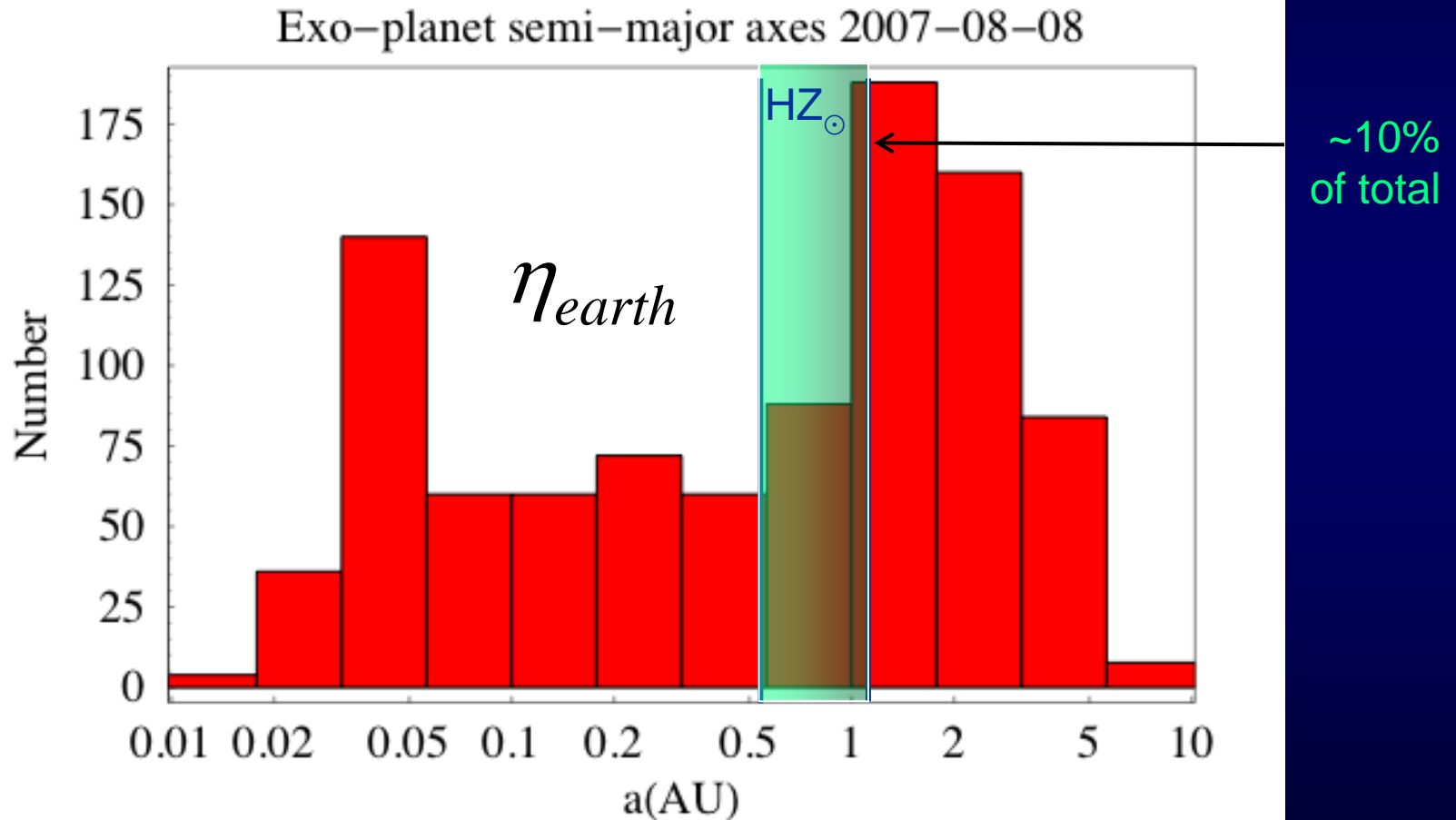


Population Samples vs. Methods

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Finding Exo-Planets between r_{in} & r_{out}

About 15% of survey stars have (Jupiter-mass) planets
About 10% of these will be in the Habitable Zone \Rightarrow 1.5%



Planet Detection & TPF

- Photon rates from exo-Earths make photometric detection straightforward with modest (2-4m) size telescopes
- Spectroscopy ($\lambda/\Delta\lambda \sim 100$) of exo-Earths could be done with ~4m telescopes with great patience and no margins
 - Large collecting areas are desirable, probably required
- Coronagraphic telescopes will have to be large (>8m) to study the habitable zones (HZ) of a good sample of nearby stars
 - At least ~8m sizes necessary to give small inner working angles
- Occulters (NWO, e.g) will have to be large (>60m) and at large distances (~600,000 km) from a space telescope for the small inner working angles (IWA) to study the HZ of nearby stars

These conclusions suggest that modest proposals (~4m-class telescopes) cannot produce credible TPF programs, and that we can consider the use of very large apertures (10 - 30m).